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Quantum Zeno effect in spontaneous decay with distant detector

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Abstract

A numerical model of spontaneous decay which is continuously observed by a distant detector of emitted particles is constructed. It is shown that there is no quantum Zeno effect in such quantum measurement if the interaction between the emitted particles and the detector is short-range and the mass of emitted particles is not zero.

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Keywords: Quantum measurement; Quantum Zeno effect; Spontaneous decay; Numerical model

1. Introduction

The quantum Zeno paradox (QZP) is the proposition that evolution of a quantum system is stopped if the state of the system is continuously measured by a macroscopic device to check whether the system is still in its initial state [1]. QZP is a consequence of formal application of von Neumann's projection postulate if the continuous measurement is represented by a sequence of infinitely frequent instantaneous collapses of system's wave function. It was shown theoretically [2] and experimentally [3] that sufficiently frequent discrete active measurements of system's state really inhibit quantum evolution such as Rabi oscillations between discrete levels. This phenomenon was named "quantum Zeno effect" (QZE). Another kind of Zeno effect is QZE during *genuinely continuous* observation of spontaneous exponential transition.

The genuinely continuous observation is a quantum measurement with permanent coupling between the device and the measured system. This coupling may be described by a time independent Hamiltonian. Some schematic models of genuinely continuous observation of spontaneous exponential transition were studied for the first time in [4], then in [5,6]. It was argued in [4] that QZE is very small or negligible, in [5] that QZE may take place in principle, in [6] that QZE take place generally and may have different signs: direct or reverse QZE.

The model of genuinely continuous observation of spontaneous exponential transition related to experiment was studied in [7]. It was the model of observation of decay by a distant detector. The general expression for perturbation of decay constant by an observation were obtained and it was argued qualitatively that QZE may take place. But calculations with the derived expression were not carried out due to technical difficulties. Another model was considered in [8,9] — the model of tunneling of an electron out of a quantum dot with the observation of transition by changing of

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electric current. It was argued in [8] that there is no QZE in this model, but later the calculations were improved [9] and conclusion was obtained that QZE may take place if the density of final states of electron depends on energy. A number of effects similar to QZE in continuous observation of decay were also studied [10–12]. General conclusion of these works was that QZE-like effects may take place but the sign of effects may be different: either slowing down or fastening up of the decay. Thus, the situation with QZE during continuous measurements of spontaneous decay is not quite clear.

Especially difficult questions are connected with QZE during continuous observation of decay by a distant detector. Let us consider, for example, a metastable exited atom surrounded by detectors which can register an emitted photon or electron when the exited state of atom decays to the ground state. While the detectors are not discharged, the information that the atom is in its exited state is being obtained permanently, therefore the system's state is being measured continuously. Could the presence of detectors influence the decay constant of exited atom?

It is impossible to describe this kind of continuous measurement by a sequence of discrete wave function collapses as was proposed in seminal works [1]. Such approach leads to the explicit quantum Zeno paradox, not effect. Instead, a dynamical description of such measurements was elaborated in [7,12]. In this approach the object system (atom), the radiation field (or emitted particle), and the device (detector of particles) are considered as subsystems of one compound quantum system. The analysis of Schrödinger equation of this compound system yields the expression for the decay constant perturbed by a given interaction W of emitted particles with detector [7,12]:

$$\Gamma = 2\pi \int d\omega\, M(\omega)\Delta(\omega - \mathcal{E}_0). \tag{1}$$

In Eq. (1) $M(\omega)$ is the sum of all transition matrix element squares related to the same energy of emitted particle ω (interaction formfactor), $\mathcal{E}_0$ is the expectation value of final energy of emitted particle. The function $\Delta(\omega - \mathcal{E}_0)$ describes the influence of observation on the decay constant. Without detectors the function $\Delta(\omega - \mathcal{E}_0)$ transforms to the Dirac's delta-function $\delta(\omega - \mathcal{E}_0)$ and Eq. (1) transforms to the Golden rule [7,12].

The dynamics of observation of decay by a distant detector is similar to the dynamics of spontaneous decay onto an unstable final state. Particularly, in the last case the decay constant perturbed by instability of final state is given by the same Eq. (1) as in the previous one [12]. The physical meaning of function $\Delta(\omega - \mathcal{E}_0)$ in the case of decay onto an unstable level is simple: this is an energy spreading of the final state of decay due to its instability [12]. Also, perturbation of decay constant takes place in this case in general. This effect is analogous to QZE. By analogy, it was supposed [7] that the meaning of $\Delta(\omega - \mathcal{E}_0)$ in the case of observation of decay by a distant detector is an energy spreading of the final states of decay due to time-energy uncertainty relation and finite time-life of emitted particle until scattering on the detector. Therefore one can suggest that the observation influences decay in accordance with the following sequence: The shorter emitted particle time-life before scattering on the detector, the wider $\Delta(\omega - \mathcal{E}_0)$, the stronger perturbation of decay constant. This argument qualitatively leads to the existence of QZE during observation of decay by a distant detector. The opposite point of view is represented in [13]. It was argued in this paper that the observation of decay by distant detector is not a quantum measurement at all and there is no QZE.

It is clear that a strong interaction W between the emitted particle and the detector is needed to obtain QZE. Hence, W is essentially nonperturbative in this problem. This feature determines the main difficulty of calculations of function $\Delta(\omega - \mathcal{E}_0)$ in Eq. (1) and, consequently, the perturbed value of decay constant. Particularly, in [7] we supposed that QZE may explain strong inhibition of the 76 eV nuclear uranium-235 isomer decay in the matrix of silver [14]. However, we had to restrict the consideration only by a qualitative analysis of Eq. (1) for this case due to difficulties of calculations of function $\Delta(\omega - \mathcal{E}_0)$.

Since it is difficult to study a realistic physical system, it is reasonable to start with some simplified models to calculate the function Δ. The aim of the present Letter is numerical investigation of Eq. (1) for a simple but not oversimplified model system. We obtain some general formalisms firstly; then introduce one-dimensional three-particle model of continuous observation of decay; then describe the numerical computation scheme for this model, and finally discuss the results of calculations.

2. General considerations

Let a compound system $S = X \otimes Y \otimes Z$ consists [1] of three subsystems X, Y, and Z. The system X ("atom") decays spontaneously from the initial exited state $|X_e\rangle$ to the ground state $|X_g\rangle$ emitting a particle Y ("electron") due to the interaction V between systems X and Y. The particle Y is initially at the ground state $|Y_0\rangle$ (electron is on the bounded state in atom) and then transits to the continuum $|Y(\eta, E_Y)\rangle$. Here E_Y is the energy of the state in the continuum and η represents all other quantum numbers. Particle Y scatters inelastically on the system Z ("distant detector") due to the interaction W between Y and Z. As a result, the system Z transits from the initial ground state $|Z_0\rangle$ to the continuum $|Z(\zeta, E_Z)\rangle$. This transition is considered to be a registration of decay. We consider that the interaction V does not effect system Z, the interaction W does not effect system X and the systems Y and Z do not interact in their ground states. Therefore, we have

$$V = V_{XY} \otimes I_Z, \qquad W = I_X \otimes W_{YZ},$$
$$W_{YZ}|Y_0 Z_0\rangle = 0, \tag{2}$$

where I_X and I_Z are the unit operators in the Hilbert spaces of corresponding systems. The Hamiltonian of compound system is

$$H = H_0 + V + W, \tag{3}$$

where

$$H_0 = H_X^0 \otimes I_{YZ} + H_Y^0 \otimes I_{XZ} + H_Z^0 \otimes I_{YX}$$

with obvious notations.

The initial state of system S at the initial moment of time $T = 0$ is

$$|\Psi_0\rangle = |X_e\rangle \otimes |Y_0\rangle \otimes |Z_0\rangle \equiv |X_e Y_0 Z_0\rangle.$$

Let us introduce the first-order correction to the eigenenergy of state $|\Psi_0\rangle$ due to interaction V:

$$\delta V_0 = \langle \Psi_0 | V | \Psi_0 \rangle,$$

and renormalized unperturbed Hamiltonian H_0 and renormalized interaction V:

$$H_0' = H_0 + \delta V_0 |\Psi_0\rangle\langle\Psi_0|,$$
$$V' = V - \delta V_0 |\Psi_0\rangle\langle\Psi_0|.$$

[1] $S = X \otimes Y \otimes Z$ means that the Hilbert space of system S is a direct product of the spaces of systems X, Y, Z.

Then Hamiltonian (3) may be rewritten as

$$H = H_0' + V' + W.$$

The initial state $|\Psi_0\rangle$ is an eigenstate of the Hamiltonian H_0' with the eigenenergy

$$\mathcal{E}_0' = E_X^e + E_Y^0 + E_Z^0 + \delta V_0.$$

The interaction V is considered to be a small perturbation, but the interaction W is not small. To obtain the decay constant of the exited state $|X_e\rangle$ it is necessary to solve the Schrödinger equation for the compound system S. It is impossible to construct the perturbation theory for W, but it is possible for V. Therefore, let us introduce the interaction picture as ($\hbar = 1$)

$$\big|\Psi_I(T)\big\rangle = e^{i(H_0'+W)T}\big|\Psi(T)\big\rangle, \qquad \big|\Psi_I(0)\big\rangle = |\Psi_0\rangle,$$
$$V_I'(T) = e^{i(H_0'+W)T} V' e^{-i(H_0'+W)T}. \tag{4}$$

Then the Schrödinger equation reads as

$$\big|\Psi_I(T)\big\rangle = |\Psi_0\rangle - i\int_0^T V_I'(t)\big|\Psi_I(t)\big\rangle\,dt. \tag{5}$$

The solution of Eq. (5) in the second order of perturbation theory with respect to V is

$$\big|\Psi_I(T)\big\rangle = |\Psi_0\rangle - i\int_0^T V_I'(t)|\Psi_0\rangle\,dt - \int_0^T dt_1 \int_0^{t_1} dt_2\, V_I'(t_1)V_I'(t_2)|\Psi_0\rangle. \tag{6}$$

Let $F(T)$ be the nondecay amplitude

$$F(T) = e^{i\mathcal{E}_0' T}\big\langle\Psi_0\big|\Psi(T)\big\rangle.$$

It follows from Eqs. (4) and (6) that

$$F(T) = 1 - \int_0^T dt_1 \int_0^{t_1} dt_2\, \langle\Psi_0|V_I'(t_1)V_I'(t_2)|\Psi_0\rangle. \tag{7}$$

For the initial region of exponential decay curve (time is not very small, not large) we assume

$$F(T) = \exp(-\gamma T) \cong 1 - \gamma T, \qquad \gamma = \text{const}. \tag{8}$$

Then the quantity $\Gamma = 2\,\mathrm{Re}\,\gamma$ is the probability of decay per unit of time (decay constant). Using Eqs. (7)

and (8), we obtain

$$\Gamma = 2\,\mathrm{Re}\int_0^\infty \langle\Psi_0|V' e^{-i(H_0'+W)t} V'|\Psi_0\rangle e^{i\mathcal{E}_0' t}\,dt. \tag{9}$$

By $v(\eta, E_Y)$ denote the matrix elements of V which cause the decay of state $|X_e\rangle$ and emitting of particle Y:

$$v(\eta, E_Y) = \big\langle X_g Y(\eta, E_Y)\big| V'_{XY}\big| X_e Y_0\big\rangle. \tag{10}$$

All other matrix elements do not effect the decay constant. Let us introduce the vector

$$|\tilde{Y}\rangle = \int d\eta\, dE_Y\, \big|Y(\eta, E_Y)\big\rangle v(\eta, E_Y). \tag{11}$$

Then, after simple algebraic transformations, Eq. (9) may be rewritten as

$$\Gamma = 2\pi \int_{-\infty}^{\infty} M(E_Y)\Delta\big(E_Y - E_Y^{\mathrm{fin}}\big)\,dE_Y, \tag{12}$$

where

$$E_Y^{\mathrm{fin}} = E_Y^0 + \omega_0 + \delta V_0, \quad \omega_0 = E_X^e - E_X^g,$$

$$M(E_Y) = \int d\eta\, \big|v(\eta, E_Y)\big|^2,$$

$$\Delta(E) = \frac{1}{\pi}\mathrm{Re}\int_0^\infty D(t) e^{-iEt}\,dt, \tag{13}$$

$$D(t) = \frac{\langle\tilde{Y} Z_0| e^{-i(H_{YZ}^0 + W_{YZ})t}|\tilde{Y} Z_0\rangle}{\langle\tilde{Y} Z_0| e^{-iH_{YZ}^0 t}|\tilde{Y} Z_0\rangle}, \tag{14}$$

$$H_{YZ}^0 = H_Y^0 \otimes I_Z + H_Z^0 \otimes I_Y.$$

It is easily shown that $\int \Delta(E)\,dE = 1$. Eq. (12) is the final formula for the decay constant perturbed by the continuous observation with a distant detector.

3. Numerical model

We consider a one-dimensional three-particle model (Fig. 1) in this section and hereafter in the present Letter. This model is connected with experiments [14] that point out to the possibility of strong inhibition of decay of uranium-235 nuclear isomer in silver. The only possible channel of decay of this isomer is the inner conversion of nuclear transition on the atomic shell. This is a radiation-less transition with emitting one of the atomic electrons. Our model represents very schematically a nuclear decay in an atomic medium by the channel of inner nuclear conversion. Here the medium plays the role of detector of conversion electrons. The medium (or detector) is represented by the only "atom" in the model. A state of a single atom may play a role of device if we are interested in a back influence of the measurement to the dynamics of measured system. Particularly, this proposition is supported by the experiments on interference of atomic beams [15]. The interference fringes are destroyed when the information about the path of atom is recorded in a single atom state.

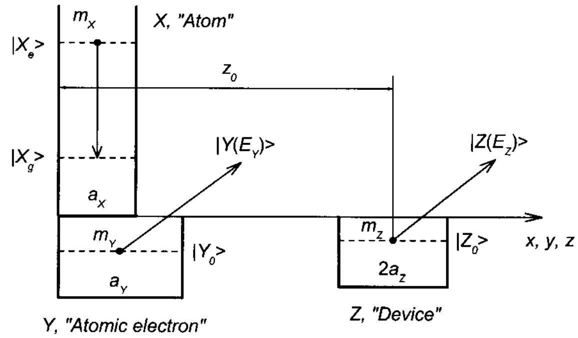

Fig. 1. The one-dimensional three-particle model of spontaneous decay with continuous observation of decay particle by a distant detector.

The systems X, Y, Z are one-dimensional rectangular potential wells. There is a single particle in each well in the initial state of system $X \otimes Y \otimes Z$. The masses of particles and the geometry of potential wells are clear from Fig. 1. We use the units such that $m_Y = 1$, $a_Y = 1$, $\hbar = 1$. The coordinates of particles X, Y, Z are denoted by x, y, z, respectively. There is an infinitely high potential wall for all particles at the point $x = y = z = 0$, consequently all particle eigenstates are nondegenerated. We consider that each particle X, Y, Z governs only by its own potential well $U_X(x)$, $U_Y(y)$, $U_Z(z)$, respectively, and by interparticle interactions.

The potential well $U_X(x)$ is a potential box with solid walls. The potential wells $U_Y(y)$ and $U_Z(z)$ are such that they contain only one bounded state for particles Y and Z, respectively. The particles X and Y

interact by repulsive δ-like potential

$$V_{XY}(y-x) = v_0\delta(y-x), \quad v_0 > 0. \tag{15}$$

This interaction causes the transition of particle X from the initial state $|X_e\rangle$ to the ground state $|X_g\rangle$ and simultaneously the excitation of particle Y from the bounded state $|Y_0\rangle$ to the continuum $|Y_e(E_Y)\rangle$. Since all states are nondegenerated, the degeneration index η may be omitted. The threshold energy for particle Y to be ionized is $E_Y^{\mathrm{thr}} = 0$. The particles Y and Z interact by Gaussian repulsive potential

$$W_{YZ}(z-y) = w_0 \exp\left[-\frac{(z-y)^2}{2\sigma_W^2}\right], \quad w_0 > 0. \tag{16}$$

The Hamiltonian of compound system $X \otimes Y \otimes Z$ is

$$\begin{aligned} H = {} & \left[-\frac{1}{2m_x}\frac{\partial^2}{\partial x^2} + U_X(x)\right] \otimes I_{YZ} \\ & + \left[-\frac{1}{2m_y}\frac{\partial^2}{\partial y^2} + U_Y(y)\right] \otimes I_{XZ} \\ & + \left[-\frac{1}{2m_z}\frac{\partial^2}{\partial z^2} + U_Z(z)\right] \otimes I_{XY} \\ & + V_{XY}(y-x) \otimes I_Z + W_{YZ}(z-y) \otimes I_X. \end{aligned}$$

The general expressions for $v(\eta, E_Y)$, $|\tilde{Y}\rangle$, and Γ (Eqs. (10), (11), and (12), respectively) now become

$$v(E_Y) = \langle X_g Y(E_Y) | V_{XY} | X_e Y_0 \rangle, \tag{17}$$

$$|\tilde{Y}\rangle = \int |Y(E_Y)\rangle v(E_Y)\, dE_Y, \tag{18}$$

$$\Gamma = 2\pi \int |v(E_Y)|^2 \Delta(E_Y - E_Y^{\mathrm{fin}})\, dE_Y. \tag{19}$$

The expressions for $\Delta(E)$ and $D(t)$ (Eqs. (13) and (14), respectively) remain unchanged.

To calculate Γ we should calculate $D(t)$. To calculate $D(t)$ we should calculate two functions

$$q(t) = \langle \tilde{Y} Z_0 | e^{-i(H_{YZ}^0 + W_{YZ})t} | \tilde{Y} Z_0 \rangle, \tag{20}$$

$$q_0(t) = \langle \tilde{Y} Z_0 | e^{-iH_{YZ}^0 t} | \tilde{Y} Z_0 \rangle, \tag{21}$$

and then find $D(t) = q(t)/q_0(t)$. We calculate $q(t)$ numerically in this Letter.

To obtain $q(t)$ the Schrödinger equation may be solved:

$$i\frac{\partial \tilde{\Psi}(y,z,t)}{\partial t} = (H_{YZ}^0 + W_{YZ})\tilde{\Psi}(y,z,t), \tag{22}$$

$$\tilde{\Psi}(y,z,0) = \tilde{Y}(y) Z_0(z), \tag{23}$$

and then the inner product $q(t) = \langle \tilde{Y} Z_0 | \tilde{\Psi}(y,z,t)\rangle$ may be obtained. It follows from Eqs. (15), (17), and (18) that $\tilde{Y}(y)$ may be represented through functions X_e, X_g, and Y_0 as

$$\tilde{Y}(y) = N Y_0(y)\left[X_g^*(y) X_e(y) - \int |Y_0(y')|^2 X_g^*(y') X_e(y')\, dy'\right], \tag{24}$$

where N is a normalization factor. Since the functions $X_e(x)$, $X_g(x)$, $Y_0(y)$, and $Z_0(z)$ are the well known eigenfunctions of one-dimensional rectangular well, it is easy to calculate the initial state (23) analytically. Note that it follows from Eq. (24) that $\tilde{Y}(y)$ is a compact wave packet near the origin of axis y. The physical meaning of this wave packet is the state of particle Y that arises virtually just after the particle excitation [7].

Eq. (22) was solved numerically. The state of the system $Y \otimes Z$ was represented by a grid wave function with zero margin conditions defined on two-dimensional equidistant rectangular grid with the same steps along y- and z-axis. Both dimensions L_Y and L_Z of calculation area were much greater than the distance z_0 from the center of device Z to the origin of coordinate system. The scheme of calculation was as follows. Let the grid wave function at the time t be $\{\tilde{\Psi}_{kl}(t)\}$, where $k = 0, \dots, N_Y$, $l = 0, \dots, N_Z$. Then the wave function at the time $t + \Delta t$ is calculated through successive four steps:

(a) The calculation of sin-Fourier transform of the grid function $\{\tilde{\Psi}_{kl}(t)\}$:

$$F_{mn}(t) = \frac{4}{N_Y N_Z}\sum_{k=1}^{N_Y-1}\sum_{l=1}^{N_Z-1}\tilde{\Psi}_{kl}(t) \times \sin\left(\frac{m\pi}{N_Y}k\right)\sin\left(\frac{n\pi}{N_Z}l\right).$$

(b) The calculation of free evolution of Fourier coefficients:

$$F_{mn}(t+\Delta t) = F_{mn}(t)\exp\left\{-i\left[\frac{1}{2m_Y}\left(\frac{m\pi}{L_Y}\right)^2 + \frac{1}{2m_Z}\left(\frac{n\pi}{L_Z}\right)^2\right]\Delta t\right\}.$$

(c) The calculation of back sin-Fourier transform that produces the free evolution of system $Y \otimes Z$ without potentials U_Y, U_Z, and W_{YZ} during time interval Δt:

$$\tilde{\Psi}'_{kl}(t+\Delta t) = \sum_{k=1}^{N_Y-1} \sum_{l=1}^{N_Z-1} F_{mn}(t+\Delta t) \times \sin\left(\frac{m\pi}{N_Y}k\right) \sin\left(\frac{n\pi}{N_Z}l\right).$$

(d) The calculation of contribution of all interactions to the evolution during time interval Δt:

$$\tilde{\Psi}_{kl}(t+\Delta t) = \tilde{\Psi}'_{kl} \exp\{-i[U_Y(y_k) + U_Z(z_l) + W(z_l - y_k)]\Delta t\}.$$

The zero margin conditions is fulfilled because of representation of $\{\tilde{\Psi}_{kl}\}$ by the sin-Fourier series.

The calculation of function $q_0(t)$ (Eq. (21)) is not difficult. This calculation may be carried out analytically or numerically by the same way as the calculation of function $q(t)$, but for $W_{YZ} = 0$. To verify our calculation schemes both ways were tested (the results were identical).

4. Results of calculations and discussion

We present the results of calculations for the following set of parameters: $a_X = 0.6$, $m_Y = 1.0$, $a_Y = 1.0$, $U_Y^0 = -5.552$, $E_Y^0 = -2.776$, $z_0 = 4.0$, $2a_Z = 1.0$, $m_Z = 0.9$, $U_Z^0 = -2.210$, $E_Z^0 = -1.0$, $\sigma_W = 0.2$, $w_0 = 20000$. Here U_Y^0 and U_Z^0 are the depths of wells U_Y and U_Z. The interaction W is short-range: $\sigma_W \ll z_0$; consequently, condition (2) is fulfilled. Also, W is strong enough for the particle Y could not be tunnelled through the particle Z and the energy of transition ω_0 is high enough to ionize Z.

The results of calculation are as follows. The function $q(t)$ is almost the same as function $q_0(t)$. The resulting function $D(t)$ is shown in Fig. 2 by the solid line. It is seen that $D(t)$ does not show a drop-down behavior, but rather shows some oscillations at long times. It is impossible to calculate the function $\Delta(E)$ numerically in this situation because integral (13) diverges, but it is clear that $\Delta(E)$ will be δ-like function. Thus, it follows from Eq. (19) that Γ is almost equal Γ_0 and Zeno effect is absent.

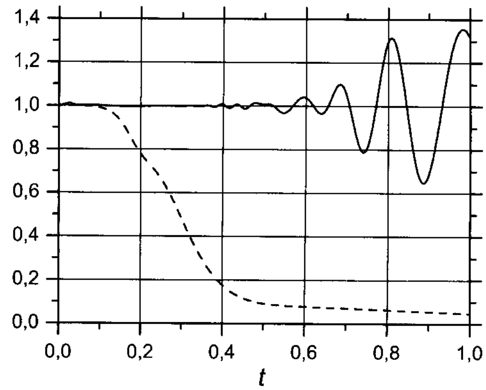

Fig. 2. The results of calculations. Solid line — $|D(t)|$; dashed line — $P_{\mathrm{sur}}(t)$.

We mentioned that it was reasonably to consider the function $\Delta(E_Y - E_Y^{\mathrm{fin}})$ in Eq. (12) as an energy spreading of the final state of decay due to a finite time life of particle Y until inelastic scattering on detector Z. Then the function $D(t)$ is the effective "decay curve" of the final state of decay in the analogy with the decay onto an unstable level [12]. But it is clearly seen from our results that it is not the case for the considered numerical model. The survival probability of the state $|Z_0\rangle$ after the decay of the system X was occur, may be written as

$$P_{\mathrm{sur}}(t) = \mathrm{Tr}\left[|Z_0\rangle\langle Z_0|\rho_Z(t)\right] = \int dy \left| \int dz\, \tilde{\Psi}(y,z,t) Z_0^*(z) \right|^2,$$

where $\tilde{\Psi}(y,z,t)$ is the solution of Eq. (20) and $\rho_Z(t)$ is the reduced density matrix of the system Z. The curve $P_{\mathrm{sur}}(t)$ is shown in Fig. 2 by the dashed line. It is seen that the survival probability decreases with time (as could be expected) and that $P_{\mathrm{sur}}(t)$ is quite different from the function $D(t)$.

Thus, our conclusions are as follows. Firstly, the functions $\Delta(E)$ and $D(t)$ in Eqs. (12) and (13) have no any simple physical sense in the context of the problem of continuous observation of decay by a distant detector. Generally, the function $D(t)$ does not mean "nondecay amplitude" of the final state of decay, and the function $\Delta(E)$ does not mean the energy spreading of decay final states. Secondly, there is no quantum Zeno effect during the continuous observation of spontaneous decay by a distant detector if interaction between emitted particle and detector is short-range and the emitted particle has nonzero mass. These results are not trivial, because the qualitative consideration based on similarity between decay onto an unstable level and observation of decay by distant detector (see Section 1) points out to the possibility of QZE in the last case. Finally, we did not consider the case of "spreaded" detector, when the wave function of detector intersects with the wave function of decay system at the initial state, and we did not consider the case of massless emitted particles. The existence of Zeno effect in these situations is meanwhile an open question.

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